DYNAMIC TEST METHOD FOR THE DETERMINATION OF THE GLOBAL SEASONAL PERFORMANCE FACTOR OF HEAT PUMPS USED FOR HEATING, COOLING AND DOMESTIC HOT WATER PREPARATION

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ABSTRACT

The necessity of innovation on the field of renewable energy systems imposes on the industry to develop faster and faster new products or product assemblies while managing perfectly the quality of the products.

In order to accelerate this process, a first version of a dynamic emulation test method has been developed.

Since the test bench emulates the building that is connected to the system being tested, the test can be carried out under “quasi”-realistic, dynamic conditions: dynamic weather conditions and occupancy profiles are used as well as a simulated building and heating/cooling system. This approach opens a large variety of possible test schedules since the simulated building, the heating system, weather conditions and occupancy can be changed freely.

A methodology for the definition of a reference test scenario is analysed in this paper, for the case of a geothermal heat pump, allowing the application of the method to other systems, climates or buildings. The difference between real annual performance (in this study the annual simulation case) and performance obtained by reduced tests using this first approach is below 5 percent for four different climates and 4 different test sequences. The test result is the monthly and annual energy consumption and performance of the system split into SPF for heating, cooling and hot water production.

A method has been developed that fits well for monthly and yearly energy figures for all modes. However, the errors of SPF values have not been reduced using this method.

Therefore, the method is, at the date of publication, being updated to further improvement the approach.

INTRODUCTION

More and more innovations appear on the market to provide multi-energy systems for space heating, cooling and domestic hot water supply. These systems can be based on solar thermal, heat pumps, biomass boilers etc. or any combination of the previous.

The necessity of innovation on this field imposes on the industry to develop faster and faster new products or product assemblies while managing perfectly the quality of the products. Prototypes and later the finalized product have to be developed and tested. Once the product on the market, standard tests exist in some cases of systems, but in most cases annual performances of the systems have to be estimated from simplified standardized test results.

In order to accelerate this process, a dynamic emulation test method has been developed and is presented in this paper on the example of a geothermal heat pump system. The aim is to prepare a testing method for heat pumps allowing the evaluation of their performances close to real, annual performances as obtained in field tests.

Emulation technique is used for control systems since the early 90’s (Haves et al, 1991). Similar approaches have already been investigated and validated for renewable energy systems for solar combisystems (Visser, 2003), (Vogelsanger, 2002), (Bales, 2002). These approaches are based on system emulation: the solar combisystem is emulated in a virtual building and simulated solar collectors.

The advantage of this approach is, that the test is carried out under “quasi”-realistic, dynamic conditions: dynamic weather conditions and occupancy profiles are used as well as a simulated building and heating/cooling system. This approach opens a large variety of possible test schedules since the simulated building, the heating system, weather conditions and occupancy can be changed freely.

A methodology for the definition of a reference test scenario is described in this paper for the application of a geothermal heat pump for heating, cooling and hot water preparation.

The test method is developed by parametric, numerical study: a typical GSHP system is modelled in Matlab/Simulink (Matlab, 2004), (Simulink, 2004) environment using the SIMBAD library (Simbad, 2004) that has already been used intensively for emulation (Riederer et al, 2001).

The development of the whole methodology is in progress. It will follow the steps listed hereunder:

- Step 1: annual simulation of a geothermal heat pump for different climates, ground types etc.;
- Step 2: development of a first test sequences by calculation of average days representing each the average of one month;
- Step 3: adjustment of the average days in order to fit the extrapolated, annual consumption by

the 12 day-test method with those calculated by annual simulation (optimisation of the test sequence);
- Step 4: validation of the method with comparing the test results of the real heat pump with monitoring results of the same heat pump.

In this paper, steps 1 and 2 are shown in order to give a first idea on the validity of the method. To date, optimisation is carried out using the Matlab optimisation toolbox in order to optimise the fit of performance (SPF) and energy figures and to perfectly manage the test sequence.

One particular problem of such a method for the geothermal heat pump is the inertia of the parts of the system (in this case the inertia of the ground). The methodology shows how to deal with this issue and to obtain a representative test methodology.

THE TEST FACILITIES

The real heat pump shall be installed on the semi-virtual test benches of CSTB in Sophia Antipolis Figure 1 shows the small test bench with a power range up to 10 kW and 4 circuits.

Figure 1: Test bench facilities with charge and discharge modules – 10kW

These test benches allows the emulation of almost any water-flowed energy-system in the power range of up to 50kW using different charge and discharge circuits. The test bench control allows the outlet temperature and flowrate being controlled following building or system simulation. Matlab/Simulink or TRNSYS is used for the numerical part of the test bench. Simulation is therefore slowed down to real time and the simulation environment enables at the same time the test bench control, system simulation (emulator) and online monitoring of the test. Outlet and zone temperature sensors are replaced by programmable resistances, also controlled by simulation.

The graphical user interface for test bench control and visualisation is shown in Figure 2.

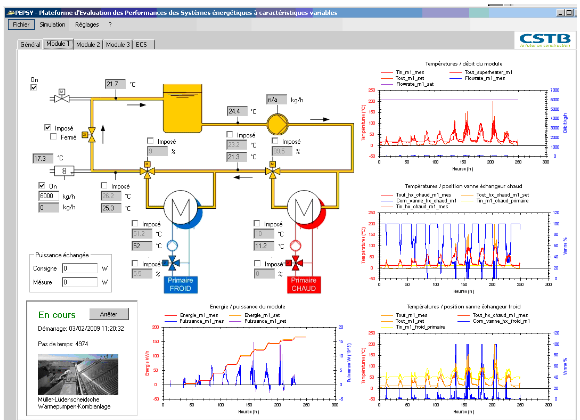

Figure 2: Graphical user interface of the test bench

The work presented in this paper does not use the real heat pump yet. This will be presented in future paper.

METHODOLOGY

As explained briefly in the introduction, the aim is to develop a 12-day test scenario with each day representing a typical day of one month. The test scenario will be a file with the following data of a time step of one hour:

- Weather data: outdoor temperature, solar direct and diffuse radiation;
- Occupant and equipment data: tap water profiles and internal gains.

The approach chosen in this paper is a mixture between annual simulation and a 12-day test in real time: the whole system including a model of the heat pump (based on identification) is simulated over one year. Each month one day (e.g. 15th day), the simulation is slowed down to real time and the numerical model of the heat pump (based on identification) is replaced by the heat pump to be tested on the test bench. (Figure 3).

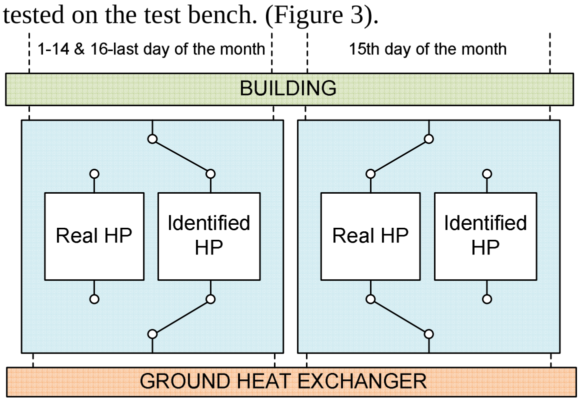

Figure 3 : Integration of real and simulated heat pump in the testing method

For the development of the test sequence, main objective in this paper, the real heat pump is replaced by a simulation model of the heat pump.
The particular problem when developing a reduced test scenario for geothermal heat pumps is the high inertia of the ground part of the system that can be either horizontal collectors or vertical boreholes. In this study, to show the validity, boreholes are considered since they present a higher inertia and thus the more difficult problem.

AVERAGE TEST DAYS

Each real-time day (one per month) of the testing sequence requires utilising specific weather data that have to be as representative as possible for the month concerned. Three methods of calculating the averages have been applied:

- 1st method: original weather data is kept for all days (original day approach - ODA);
- 2nd method: original weather data of the 15th day of each month is replaced by averaged values of all days of the month (average day approach - ADA);
- 3rd method: the weather data of that day of the month where the average energy demand of the whole month has been reached has been replaced with the averaged values of all days of the month. Depending on the season, either heating or cooling demand is chosen as the reference (average momentum approach - AMA);
- 4th method: the weather data of that day of the month (and the day before) where the average energy demand of the whole month has been reached has been replaced with the averaged values of all days of the month with energy demand. Depending on the season, either heating or cooling demand is chosen as the reference (weighted momentum approach - WMA).

In all cases, the typical day, with hourly data, is determined as follows:

$$\overline{X} = \left(\overline{x}_1 \ldots \overline{x}_{24}\right) = \frac{1}{n_d} \times \sum_{i=1}^{n_d} X(i)$$

where $\overline{X} = \left(\overline{x}_1 \ldots \overline{x}_{24}\right)$ are the 24 (hourly) values of the typical day, $X(i)$ are the 24 values of the i^{th} day of the month and n_d is the number of days of this month to be considered (either all days or all days with energy demand, depending on the method).

This operation is realised on the weather data required by the simulation model, such as air dry bulb temperature, direct normal radiation, diffuse horizontal radiation. Figure 4 shows the results for the outdoor air temperature for the case of the climate of Trappes, France.

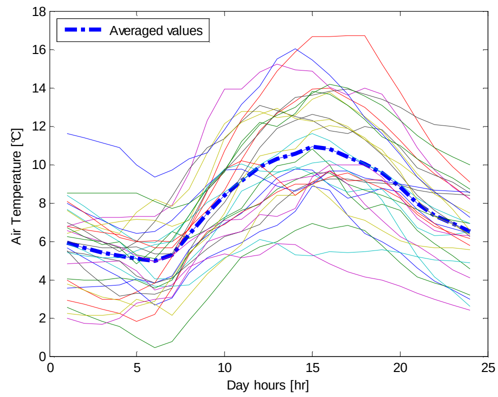

Figure 4 : Daily air temperatures of the original weather file (April, Trappes) and ADA day

IDENTIFIED HEAT PUMP MODEL

Since the test is in fact an annual simulation with only 12 days in real time, the main part of the simulation has to be carried out using a model of the heat pump. This allows the borehole as well as the building to be kept, in-between the real tests, at a temperature level that is as close as possible to that in real conditions.
It has been chosen to use an identification approach. The steps of the method are explained hereunder for the 2nd method (ADA) where the 15th day is replaced:

- in the first 14 days of the year the model parameters are those taken from manufacturer data or from a preliminary test;
- during the 15th day, the real heat pump (in this case a simulation model of the heat pump) is used;
- after each real time day where test data is available, a new polynomial model is identified representing the "real" performance data of the heat pump;

The approach is illustrated in Figure 5 for the whole testing period.

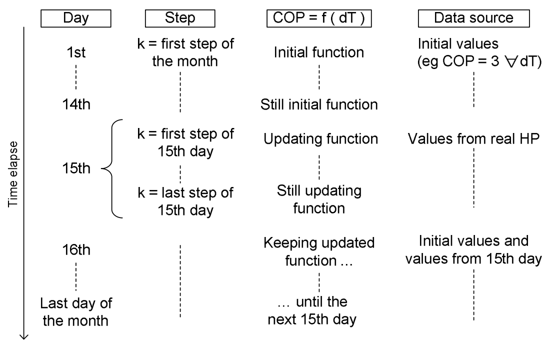

Figure 5 : Identification procedure for the heat pump

In this way, it is possible to simulate the whole system including the boreholes as close as possible to the real case and, at the end of the test, to dispose of a

heat pump model based on the total available testing data of the heat pump.
In this first approach, the identification model (steady state) is based on a look up table with testing data available. The look up table relates a table of i temperature differences (the value of i=10 – between 0 and 40 K - has been chosen for this study) between evaporator and condenser side to the corresponding COP, from measurement. The COP is used for heating and cooling relating always condenser power to the electrical power of the heat pump. In order to keep the amount of data on a reasonable level, the look-up table if based on weighting factors in order to update the values of the i COP and related temperature differences. At each time step, that value in the table at the corresponding to the actual value of the temperature difference is updated as follows:

$$\overline{COP_t}(\Delta\theta_i) = \frac{\overline{COP_{t-1}}(\Delta\theta_i)\cdot n_{data,t-1,\Delta\theta_i} + COP_t(\Delta\theta_i)}{n_{data,t,\Delta\theta_i}}$$

$$\overline{\theta_{t,i}} = \frac{\overline{\theta_{t-1,i}}\cdot n_{data,t-1,\Delta\theta_i} + \theta_{t,i}}{n_{data,t,\Delta\theta_i}}$$

with $n_{data,t,\Delta\theta_i} = n_{data,t-1,\Delta\theta_i} + 1$

$\overline{COP_t}(\Delta\theta_i)$ the average value of the COP at time t and the related temperature difference $\Delta\theta_i$

$COP_t(\Delta\theta_i)$ the value of the COP at time t and the related temperature difference $\Delta\theta_i$

$n_{data,t,\Delta\theta i}$ the number of measured values of $COP_t(\Delta\theta_i)$ at time t

$\theta_{t,i}$ the updated temperature difference at point i

The look-up table starts with values corresponding to those obtained from manufacturer data. It is then improved using the equation above for each measured point (every 5 seconds of the real test). The values that are not yet identified are interpolated from measured points at each time step. COP values outside the identified range are fixed to the maximum COP in the identification table.

In future steps the use of a dynamical model, also obtained using identification, will be tested, in the case that the real tests show this need.

MODELLING OF THE GSHP SYSTEM

The whole system model is based on Matlab/ Simulink environment using the SIMBAD toolbox (Simbad, 2004). The system includes the following components (Figure 6):

- Building part (building, floor heating system, domestic hot water tank, zones control, occupants, ventilation and equipment, hydronic network);
- Heat pump part (Real heat pump, identified heat pump);
- Borehole heat exchanger part.

The modelled building is based on a typology of French buildings and is called Mozart with about 100 m² floor area. The building is simulated as a one-zone model with temperature ON/OFF control of heat pump and floor heating and cooling at set points of 20 and 26 °C respectively. The set point for the storage tank for domestic hot water is 45 °C, also using the heat pump.

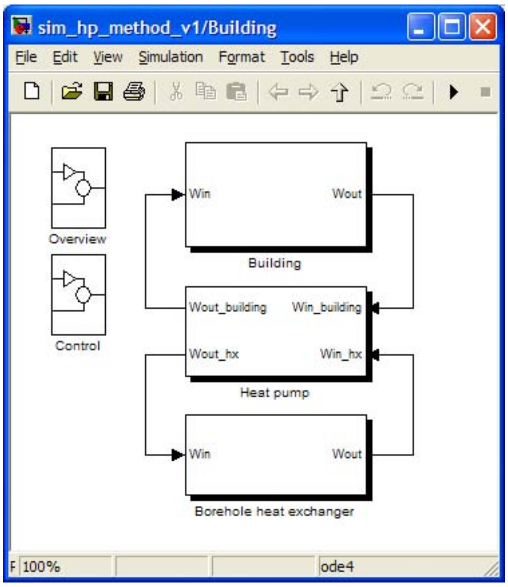

Figure 6 : First layer of the Simulink model of the complete GSHP system

Occupancy and equipment (lighting, other equipment) is chosen as a simple profile for a 4-person household starting from 7 AM to 8 PM on each day. Hot water tapping profile is based an specific water draws in-between 80 and 600 liters/hour.
The heat pump part is modelled as already described in the section on the methodology: depending on the days, the heat pump model is either the “real” heat pump or the identified heat pump model. The implementation in Simulink environment is shown in Figure 7.

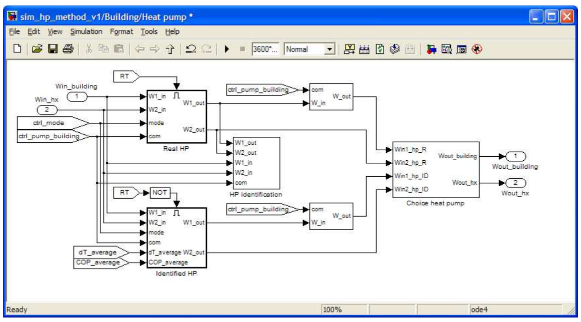

Figure 7 : Heat pump modelling (real and identified heat pump)

The “real” heat pump (in this case simulated) is raplaced by a polynomial model following the law of the Carnot COP with a constant efficiency of 30%. In order to represent real characteristics of the heat pump and measurement errors, a random error of +/- 0.5 is applied on the COP values during simulation. The relationship between the average temperature difference between evaporator and condenser inlet and the COP is shown in Figure 8.

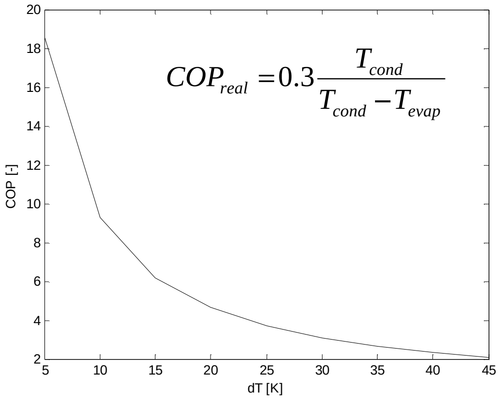

Figure 8 : Polynomial of the heat pump model

Condenser and evaporator outlet temperatures are then calculated as follows:

$$T_{cond,out} = T_{cond,in} + \frac{P_{nom} \cdot COP}{\dot{m}_{fl} \cdot Cp_{fl}}$$

$$T_{evap,out} = T_{evap,in} - \frac{P_{nom} \times (COP - 1)}{\dot{m}_{fl} \times Cp_{fl}}$$

with P_{nom} the nominal power of the heat pump
Cp_{fl} the specific heat capacity of the fluid.

The heat pump model is used in reversible mode: it uses the condenser side for space heating (floor heating) and domestic hot water preparation and the evaporator side for cooling. Hot water preparation has the priority on space heating and cooling, allover the year. Both heat pumps are controlled (with only one active depending on the day of the month) using ON/OFF control depending on the room temperature sensor measuring the average of room air and radiant temperature.

The ground heat exchanger model is based on a three dimensional, rectangular grid of the ground, coupled to a model of an integrated U-pipe or double U-pipe, which will be presented in a future paper. It is possible to define several ground layers with different thermal properties (thermal conductivity, heat capacity and density). Single boreholes or borehole fields can be simulated.
In this study, a single borehole of 120 meters (for all climates) has been modelled with 140mm diameter and with the ground physical properties of gravel, over the whole depth of the borehole.
All pumps for space heating and cooling, domestic hot water preparation as well as the boreholes are controlled in the same way as the heat pump.

ANALYSIS OF THE DEVELOPED METHODOLOGY

In order to validate the methodology, the results of all four testing methods are compared to the annual simulation of the reference case on four different locations with different climates (Trappes, Nice, Nancy and La Rochelle).

The comparison of the methods is divided into two parts:

- Comparison of energies delivered by the heat pump (for each mode);
- Comparison of SPF values (for each mode).

It is important to compare these both types of figures at the same time since an accurate SPF value does not necessarily mean that the days of the test method are selected in an appropriate way. Positive and negative errors can (and do, as shown in the results) hide problems in the method, if only SPF values are considered. The best selection would mean that at the same time, energy and SPF values fit all both.

The calculation of energies and the SPF is based on the following assumptions:

- the reference case that has been defined as the yearly simulation of the global system as described in the previous section. Energy and SPF figures are based on the results of the whole year.
- 1st - 3rd method (ODA, ADA and AMA): the yearly energy and performance data for all three modes is extrapolated from the monthly results by multiplying energies with the number of days of each month;
- 4th method (WMA): the yearly energy and performance data for all three modes is extrapolated from the monthly results by multiplying energies with the number of days with energy demand in the corresponding month.

Analysis of energy delivered by the heat pump

Figures 9-15 show a selection of results in terms of energy delivered by the heat pumps in the different modes. The climates selected for presentation are those of Nancy (heating demands dominating and some cooling in summer) and Nice (equilibrated demands between heating and cooling).

The case of domestic hot water production is only shown in one case (Nancy) since the results are almost identical for all four climates (Figure 15).

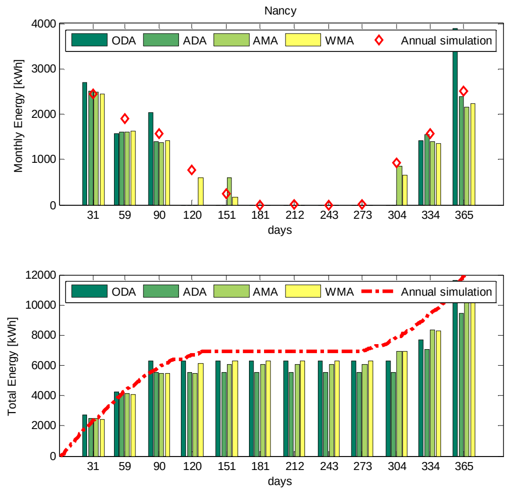

Figure 9 : Energy production of the heat pump for heating – location: Nancy

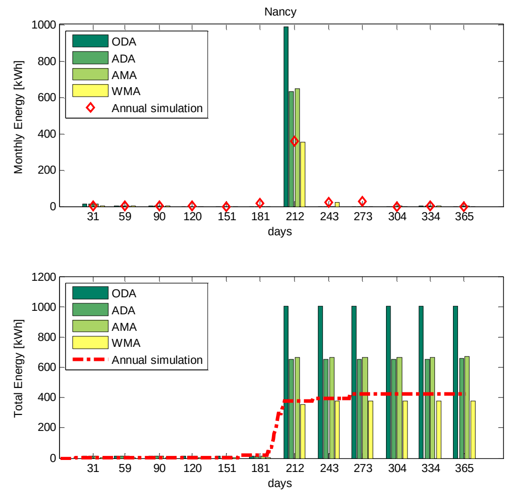

Figure 10 : Energy production of the heat pump for cooling – location: Nancy

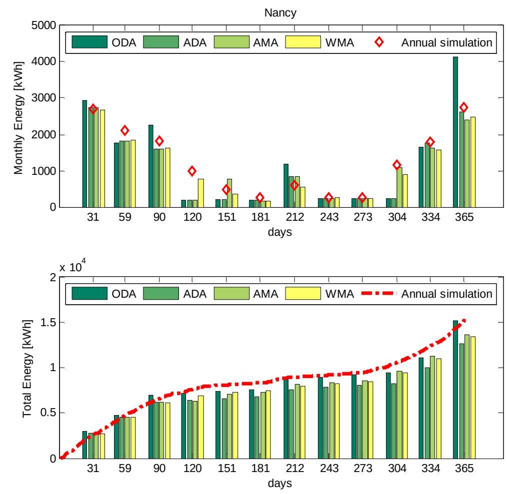

Figure 11 : Total Energy production of the heat pump – location: Nancy

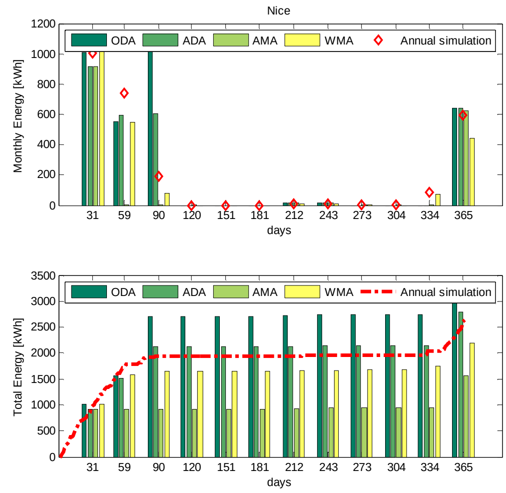

Figure 12 : Energy production of the heat pump for heating – location: Nice

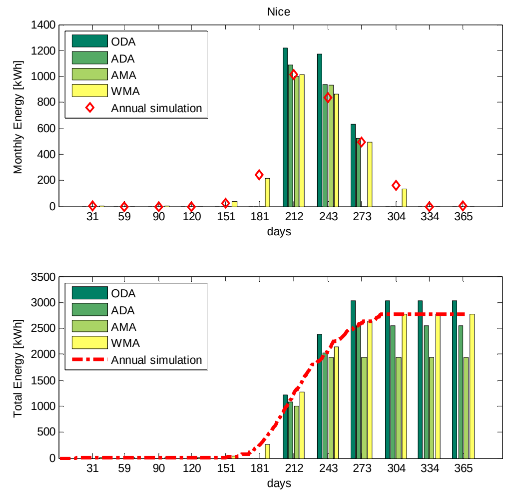

Figure 13 : Energy production of the heat pump for cooling – location: Nice

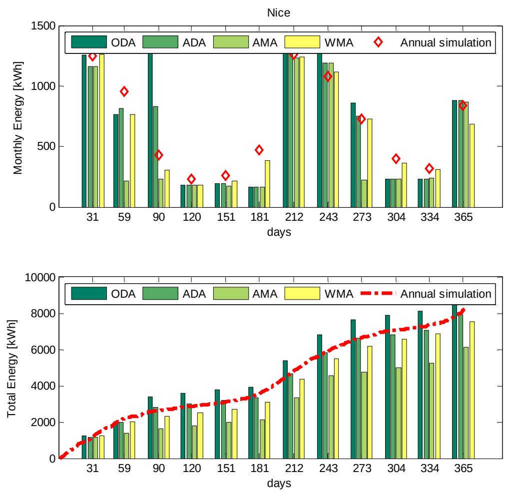

Figure 14 : Total Energy production of the heat pump – location: Nice

The four methods, compared to the reference, can be characterised as follows:

- the ODA method significant differences in heating and cooling mode for particular months. However, if the global energy is considered, these differences are compensated between over- and underestimated months and modes.
- The ADA method reduces the particular errors of the ODA method since the real test day corresponds to the average conditions of the month. However, the monthly errors are still non-negligible. Global results over the year and all modes agree almost as good as using the ODA method.
- The AMA was supposed to fit better as the two first methods. The presented figures show the opposite, this method is not able to improve the fit. More detailed studies of phenomena that are not presented here showed that one main difficulty of the method is that the preceding day (or days) of the selected, weighted test day, has a significant impact on the result (this is also valid for all other methods).
- The WMA has been proposed in order to overcome the problems that have been observed. The method does not, as all three other methods do, show significant differences in particular months. Almost all observed months show very good agreement and the global result can be qualified as good as the others.

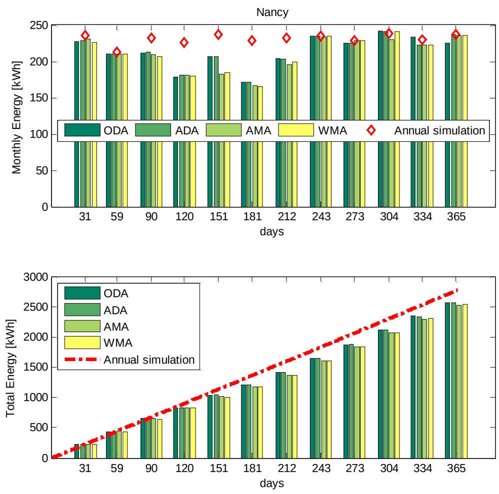

Figure 15 : Energy production of the heat pump for domestic hot water preparation – location: Nancy

In the case of DWH (Figure 15), the differences are smaller since the water tapping profile is based on a daily profile.
As a global conclusion of this comparison can be stated that the ODA show surprisingly good agreement. However, if monthly data is considered, the results differ significantly. The WMA improves the differences, even if the global results seem not to fit better as using the ODA.

<u>Analysis of SPF values of the GSHP system</u>

If performance figures (SPF) are compared, the result is different. Four SPF values have been defined for the comparison in order to get a better overview:

- SPF for space heating only
- SPF for space cooling only
- SPF for DHW preparation only
- Global SPF

The calculation is, in all cases, based on the energy delivered by the heat pump for the specific use divided by the electric energy for the heat pump itself and the pumps on the borehole side (that can be evaporator or condenser). Pump consumptions on in the building side are not considered since they would be similar in other cases of heating or cooling systems. Table 1 – 3 present the results for the three specific SPFs, for all locations.

In the heating case, the SPF values for all climates are nearly identical, which shows the advantage of a ground source heat pump. The temperature differences are moderate and almost constant throughout the year.
Concerning the methods, the ODA fits very well for all climates. The other methods cannot improve the results and even increase the difference to the reference. The only exception is the climate of Nice where the WMA improves the fit.

In the cooling case, the WMA improves all cases except Trappes (identical). This climate is not important since there is only one day where the heat pump is used for cooling during the year. This also explains the values that seem wrong (the identification has not worked properly since no data points are available).

For the SPF concerning DHW production, the results agree very well in all cases with differences of up to 2.6%. This could be expected, since the water tapping profile is the same for each day, the extrapolation from 12 to 365 days is thus only a multiplication issue.

If the global SPF is considered, the ADA and AMA method fit better than the ODA. The WMA that showed best results in almost all cases if energy is considered fits not as good as the other methods when the SPF is compared.

SPF - Heating	La Rochelle	Nancy	Nice	Trappes
SPF – Annual simulation	3.74	3.73	3.77	3.74
SPF-12 ODA method [-]	3.93	3.68	4.14	3.79
Difference with SPF[-]	0.18	-0.05	0.37	0.05
Relative error [%]	4.93	-1.23	9.95	1.33
SPF-12 ADA method [-]	3.97	3.81	4.15	3.89
Difference with SPF[-]	0.23	0.08	0.38	0.15
Relative error [%]	6.07	2.25	10.04	3.97
SPF-12 AMA method [-]	3.99	3.87	4.16	3.90
Difference with SPF[-]	0.25	0.14	0.40	0.15
Relative error [%]	6.69	3.64	10.50	4.11
SPF-12 WMA method [-]	4.01	3.87	4.10	3.92
Difference with SPF[-]	0.27	0.14	0.33	0.18
Relative error [%]	7.15	3.70	8.82	4.70

Table 1: SPF values for heating for all four climates

SPF - Cooling	La Rochelle	Nancy	Nice	Trappes
SPF – Annual simulation	3.06	3.05	2.96	3.11
SPF-12 ODA method [-]	3.14	3.06	2.91	0.64
Difference with SPF[-]	0.08	0.01	-0.06	-2.47
Relative error [%]	2.59	0.33	-1.96	-79.33
SPF-12 ADA method [-]	3.18	3.20	2.95	0.65
Difference with SPF[-]	0.12	0.15	-0.02	-2.46
Relative error [%]	3.79	5.07	-0.58	-79.16
SPF-12 AMA method [-]	3.19	3.21	2.93	0.72
Difference with SPF[-]	0.13	0.16	-0.04	-2.39
Relative error [%]	4.25	5.33	-1.27	-76.90
SPF-12 WMA method [-]	3.10	3.11	3.01	0.64
Difference with SPF[-]	0.04	0.06	0.05	-2.47
Relative error [%]	1.34	1.98	1.57	-79.55

Table 2: SPF values for cooling for all four climates

SPF - DHW	La Rochelle	Nancy	Nice	Trappes
SPF – Annual simulation	2.10	2.07	2.16	2.08
SPF-12 ODA method [-]	2.06	2.03	2.14	2.02
Difference with SPF[-]	-0.04	-0.04	-0.02	-0.05
Relative error [%]	-2.05	-2.07	-0.94	-2.63
SPF-12 ADA method [-]	2.06	2.03	2.14	2.03
Difference with SPF[-]	-0.05	-0.04	-0.02	-0.05
Relative error [%]	-2.16	-2.10	-0.84	-2.41
SPF-12 AMA method [-]	2.07	2.02	2.13	2.03
Difference with SPF[-]	-0.03	-0.06	-0.02	-0.05
Relative error [%]	-1.59	-2.66	-1.13	-2.40
SPF-12 WMA method [-]	2.07	2.03	2.14	2.04
Difference with SPF[-]	-0.03	-0.05	-0.01	-0.04
Relative error [%]	-1.38	-2.24	-0.65	-2.07

Table 3: SPF values for DHW for all four climates

SPF - Global	La Rochelle	Nancy	Nice	Trappes
SPF – Annual simulation	2.97	3.24	2.80	3.20
SPF-12 ODA method [-]	3.05	3.20	2.93	3.21
Difference with SPF[-]	0.08	-0.04	0.13	0.02
Relative error [%]	2.79	-1.16	4.69	0.37
SPF-12 ADA method [-]	2.96	3.21	2.88	3.20
Difference with SPF[-]	-0.01	-0.03	0.08	-0.01
Relative error [%]	-0.39	-0.79	3.02	-0.16
SPF-12 AMA method [-]	2.99	3.28	2.70	3.23
Difference with SPF[-]	0.02	0.04	-0.10	0.03
Relative error [%]	0.53	1.29	-3.55	0.97
SPF-12 WMA method [-]	3.14	3.29	2.94	3.28
Difference with SPF[-]	0.17	0.06	0.14	0.08
Relative error [%]	5.72	1.74	5.05	2.45

Table 4: Global SPF values for all four climates

In order to better understand the phenomena, a more detailed analysis is ongoing in order to fit at the same time energy and SPF figures and to obtain a robust method.

To finalise the method, optimisation technique will be used in order to improve the test sequence and to reduce the errors.

One other improvement of the method is the use of the annual simulation result of the identified heat pump model. This has not tested in this study since this would need also the identification of the control of the heat pump (which is based on either room temperature or phenomena that are more complex).

The method does at that time not use the real heat pump. This will be done in the next step in order to validate the test method against real monitoring.

FUTURE PERSPECTIVES

The results showed acceptable agreement between the reference cases and the test of the heat pump in a 12 day test sequence. However, from a scientific point of view, the results are deceiving since the calculation of the 12 test days did not improve test results for energy and performance figures.

The next step, which is currently in progress, is to define a better test sequence to fit at the same time energy and performance (SPF) figures.

Once this sequence is optimised, the real heat pump will be compared in the 12 day sequence with an annual monitoring of the same heat pump. These results will allow validating the method.

CONCLUSION

The paper showed the development of a new testing method for ground source heat pumps that is based on system emulation techniques. The advantage of such a method is that the system is tested in dynamic and non-nominal conditions. This is currently not the case since Cop and EER figures for heat pumps are evaluated in steady state conditions and extrapolated using simplified methods. The result of such a test will thus be more representative of the real performance since heat pump cycles and real temperature variations on evaporator and condenser side are considered.

The method has been detailed and the results showed good agreement in terms of energy delivered by the heat pumps. Performance results (SPF) on the other hand fit less with the newly developed method and the error achieves 5-6% in the worst cases. Therefore, optimisation is currently in progress to improve the test sequence and to fit at the same time performance and energy figures.

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